MANAV RACHNA INTERNATIONAL UNIVERSITY

Research Plan
For
Ph. D. Programme 2009-10

TITLE: Protection and Health Monitoring of IGBT Based PWM Inverter Fed AC Drive Systems

DEPARTMENT OF ELECTRONICS & COMMUNICATION

FACULTY OF ENGINEERING & TECHNOLOGY

Submitted by:
Name: SANJANA MALHOTRA
Registration No. : 09019990021

Supervisor
Name: Dr. M. K. Soni
Signature:
Designation: Exec.Dir & Dean,FET,MRIU

Co-Supervisor
Name: Dr. C. M. Bhatia
Signature:
Designation: Prof (Rtd), IIT, Delhi

ABSTRACT

Recent developments in the field of microelectronics and Power Semiconductor Devices (PSDs) have made possible the widespread application of inverters in Variable Speed Drives (VSD), UPS Systems, Power Converters, Switched Mode Power Supplies, Switched Mode Power Amplifiers and Active Power Filters including Flexible AC Transmission Systems (FACTS) devices and their controls. Over the past three decades, the Power Semiconductor Devices are being extensively used for various industrial, commercial and renewable energy applications including defense applications. As such, the reliability of Power Electronics equipment is assuming extreme importance. Since the PSDs are very sensitive to conditions like over current, over voltage, rate of change of voltage, rate of change of current, short circuits etc., the improvement in reliability of the Power Electronics equipment is of paramount importance. However, a common fear that prevails among the potential industry users is about Power Electronic equipments' in-adequate Protection and Health Monitoring. This inhibition especially in heavy current control either limits the wide range of application of such devices and circuits, or involves heavy costs. As such, full techno-economic exploitation of the potential of Power Electronics for industrial productivity and energy saving has been somewhat restricted. Although, the factors of inbuilt redundancy, higher safety margins in PSD ratings, and least fault processing time have been widely exploited to improve reliability; it involves higher costs. This synopsis presents the techno-economic design and its implementation of protection circuits for IGBT based Voltage Source PWM Inverters and Health Monitoring of Variable Speed AC drives for applications such as rolling mills, pulp and paper mills, traction etc.

Keywords- PWM Inverters; Protection; Power Semiconductor Devices; IGBT; Health Monitoring ; Single-Phasing; Short-circuit fault; Current Limit; Variable Speed Drives.

CONTENTS

S. No.	Description	Page Nos.
1.	Introduction	1
2.	Literature Review Status of PWM Inverter Fed Induction Motor	2 - 4
3.	Description of the Broad Area/Topic Induction Motor Variable Speed Drive (VSD) Schemes PWM Modulation Techniques Existing Protection Schemes	4 - 10
4.	Problem Identification/Objectives	10 - 11
5.	Methodology To Be Adopted	11
6.	Proposed/Expected Outcome of the Research	11
7.	Proposed Time Frame	11 - 12
8.	References	12 - 15

1. Introduction

The operational reliability and robustness of Power Electronics Devices (PSDs) Circuits and Systems, as compared to those of conventional Electrical Equipment and Systems has been a subject of great concern for the designers and application engineers. This has been mainly due to very low thermal and surge withstand capability, rate of change of voltage as well as rate of change of current of the PSDs, as compared to those of electrical machines, transformers and other power system equipment [2-4,9-12,14,26]. As such, the system reliability of Power Electronics has been rather vulnerable ever since its inception. The PSDs especially the IGBTs attracted importance from protection point of view in all Industrial, Commercial, Aerospace, Domestic and Military applications [11,21,26,40-42]. It has therefore become essential for system designers to get complete and true knowledge about the protection of Power Semiconductor Devices and Health Monitoring of inverter systems used therein [5,16,21,30-32,34-37,44]. From the point of view of Protection, Health Monitoring, Improved System Performance and Fault Diagnosis & its Control, the research investigations are being pursued to report the new systems thus designed.

The work reported in this dissertation attempts to analyze, design, develop, investigate and suggest a systematic approach into the protection of Power Electronics Devices and equipment e.g., Voltage Source PWM Inverters that are used for the control of Variable Speed Induction Motor drives and also to monitor and control the system faults for Induction motor Health Monitoring, that generally take place. Significant among these are Short-Circuit, Single-Phasing, Current-Limit, Voltage Drop, Sudden Loss of Power and re-application. The design, development and implementation of the newly proposed Protection and Health Monitoring system is envisaged to be done in the laboratory and shall be extensively tested and reported in this dissertation.

2. Literature Review

Although, some publications are available in the area of Power Semiconductor Device, Protection and Health Monitoring of Variable Speed AC Drives, only a few of the published papers are relevant and are reported in the list of references [30-32,35,41,44].

The literature published by the authors [1,6-8,10-11,15,30-32,36] have formed the base of the proposed dissertation entitled *"Protection and Health Monitoring of IGBT Based PWM Inverter Fed AC Drive Systems"*. However, further work carried out by Dr. C. M. Bhatia et al on PWM inverters [17-19,23-25,34,36,37], Variable Speed AC Drives [16,20,27-29] and Power Electronics & Protection Systems [34,35,39], at the Indian Institute of Technology Delhi and at Manav Rachna College of Engineering, Faridabad, has been very comprehensive and makes the backbone of the proposed research investigations.

2.1 Status of PWM Inverter Fed Induction Motor

Induction Motor has been established as the workhorse of industry ever since the 20^{th} century. Although, the recent developments in *Power Electronics* have brought forth some very significant drive alternatives like the *Switched Reluctance Motor*, *Permanent Magnet* and *Brushless DC Motor*, these have not yet become very popular and cost effective for a wide range of application. The widespread use of induction motor is still economical as well as popular and is likely to continue for the next few decades. The induction motor, especially the Squirrel Cage Rotor type is mostly popular in the lower horse power ranges; while the Slip Ring type is common for higher horse power ranges as well as to meet certain specific torque requirements like that of Cranes and Hoists applications. The squirrel cage motors are economic, robust, compact, and highly efficient. These motors are practically maintenance free and can be designed in the damp-proof, dust-proof and also flame-proof enclosures [2-4,12-14,21,22]. More than 90% of motors produced worldwide are of Squirrel Cage type and this trend is likely to continue further. Tables-1 and 2 give a brief summary of a variety of AC and DC drives for variable speed operation and principal R & D research areas thereof respectively.

Table-1: Types of Variable Speed Drives

DC Drives	About 50% of all drives (above 1 KW) are DC motor drives, for wide speed control range and fast response time.
AC Drives Range	Type of AC Drives
Up to 5 KW	Voltage Controlled induction motor is preferred.
Up to 100 KW	Variable Voltage Variable Frequency Inverter with either quasi-square or PWM output as per the performance requirement.
Up to 500 KW	PWM inverter driven induction motor using GTOs, BJTs or IGBTs. All these are generally microcomputer controlled.
Up to 5 MW	PWM inverter driven induction motor using thyristor. GTOs/IGBTs gradually replacing thyristors with Microprocessor based control.
All large drives beyond 2 MW	Usually either Inverter fed synchronous motor, or Cycloconverters based doubly fed induction motors or slip-energy recovery systems or Vector Controlled induction motors.

Table-2: Variable Speed Drives - Principal Areas of R & D.

Inverter Control Strategies	Harmonic elimination and reduction. Sophisticated variations of PWM inverters. Field orientation control or Vector control of air-gap field & stator mmf using real-time computation.
Variable Speed Drive Control	Scope for use as a sophisticated controller, to eliminate unnecessary mechanical components.
Improvements of PSDs	Present Devices that are popular are IGBT, GTO, MOSFET, BJT, MOT, SIT, SITH. Composite devices are under development e.g. MCT, SIT, SITH & MOT which are promising. Improvements in ratings are taking place regularly.
Unconventional motor configurations	Switched reluctance motor. Permanent magnet brushless DC motor. Disk drives (spindle motor) and motors from high energy permanent magnet materials (Neodymium iron even better than samarium cobalt).

A properly constituted Voltage Source PWM Inverter fed Induction Motor drive using Power Semiconductor Devices (PSDs) coupled with a squirrel-cage rotor motor, forms the most ideal variable speed drive for a variety of industrial applications [5,7,8,10,15]. The work reported in this dissertation therefore concentrates on IGBT based Voltage Source PWM Inverters as the base for general protection and hence the development of various circuits for the Health Monitoring of Squirrel Cage as well as Wound Rotor Induction Motors for Variable Speed Drive applications.

3. Description of the Broad Area/Topic

The general area of "*Protection and Health Monitoring of IGBT Based PWM Inverter Fed AC Drive Systems*" lies in the broad area of Power Electronics**.** However, since we envisage designing and developing such systems for the Variable Speed AC Drive Systems and its health monitoring, we need to mention Electrical Drives too as our area of knowledge. Ever since the advent of Thyristors in mid 1960's (over the past four decades), the field of Power Electronics has become very popular in almost all Industrial applications; whether it may be Electrical, Electronics, Chemical, Textile, Mining, Shipping, Aerospace etc [7,8,10,1121,30,31.36,37,41]. The main concern of system designers and application engineers has been the task of appropriate integration of heavy electrical equipment like motors, generators, transformers etc., which inherently possess a rather heavy fault mode and overload/thermal withstand capability; with very fragile small size and tiny Power Semiconductor Devices (PSDs). Although, Power Semiconductor Devices used in Inverter, Converter, Chopper have their heat sinks generally designed with fairly liberal safety margins (almost 100% reserve), so that the nominal power (with fluctuations, transients, harmonics etc.,) can be supplied to the mains, under the extreme limits of operating conditions; the system designers even then take a very pessimistic view and estimates of the AC/DC mains supply system conditions and of the battery chargers (if used). The tolerance limits of the IGBT ratings etc., as well as of the ambient weather conditions e.g. temperature, humidity, dust, acidic and alkaline fumes etc., need very special considerations from Power Electronics and device viewpoint [4,9,11,26,32,33,36,38,40-44]. The system designer should therefore be extra careful, especially when the associated Power Electronics and electronics circuits are installed open to sky, in the mines, under the locomotive and coaches, in lofts and in poorly ventilated spaces within the industrial premises.

Further, it may be emphasized that these Power Semiconductor Devices inherently have limitations of very low thermal mass and extremely low surge withstand capability, as compared to that of the heavy Electrical Equipment [9,26,36,38,42]. Hence, there has arisen the need for the design, development and study of more versatile and fast acting protection system, in conjunction with large safety margin ratings to ensure system reliability vis-à-vis the costs of device failure leading to disruption in production and hence further losses.

3.1 Induction Motor Variable Speed Drive (VSD) Schemes

The inverter circuit scheme generally used with Variable Speed Drives (VSD) can be arranged in the most general form as shown in figure 1. The three-phase supply from the AC mains is converted to DC through a set of Power Semiconductor Devices (PSDs) represented by rectifier block marked '1' in figure 1. These PSDs could be either controlled or uncontrolled: either voltage gated or current gated [1,5]. The choice of PSDs e.g., diodes, SCRs, BJTs, IGBTs, MOSFETs or GTOs depends upon the specific requirement and rating of the inverter. A reference to this effect may be made to Tables-1 and 2.

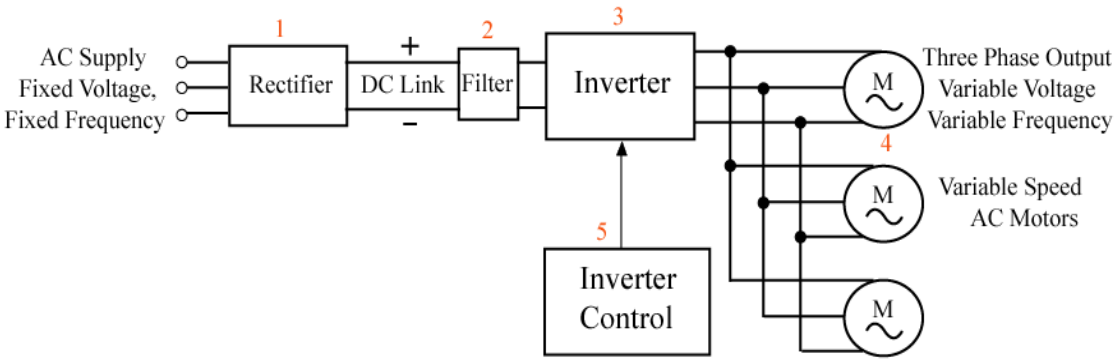

Figure 1: Block Diagram of a Basic Variable Frequency Variable Voltage Output Circuit

Since the output of '1' contains harmonics ridden voltage over the desired average DC value, there is a standard practice to filter this voltage by the filter block '2' as shown in figure 1. The output of '2', which is a filtered DC is made to switch Power Semiconductor Devices sequentially by inverter block '3', to generate a three phase AC output. This block is suitably designed with a set of PSDs to accomplish the necessary switching either to obtain a square or a quasi-square or a PWM output, as the case may be.

In order to be able to run the VSD, an induction motor in this case, the inverter circuit must have the capability to meet the following minimum requirements:

- Adjustment of output frequency.
- Adjustment of output voltage.
- A relationship of V/f ratio maintained as per drive requirement.

These controls are suitably designed and developed to be done consistent with the requirements of square, quasi-square or near sinusoidal and sinusoidal output. However, as mentioned above, the choice of output to be either square, quasi-square or near sinusoidal depends upon the horsepower rating as well as drive performance requirement as demanded by a particular application [17-19,23-25,27,36,37].

3.2 PWM Modulation Techniques

The PWM technique is further divided into two major classes - Periodic Modulation and DC Level Modulation (also known as 'on – off' modulation or variable duty ratio modulation). The PWM technique, in which the modulating signal is selected to be a periodic waveform, is known as Periodic Modulation.

The two signals i.e., the carrier and reference are compared and the crossing points of these are collected for the gating of PSDs. These crossing points are also known as *firing coordinates*. While the control of output voltage is achieved through the *Modulation Index 'M'* which is the ratio of peak of *reference signal* to the peak of *carrier signal* (A_0/Ac); the control of output frequency is done through the *carrier ratio 'I'*. The ratio *'I'* is the ratio of carrier signal frequency to the reference signal frequency (f_c/f_o). Thus, by properly selecting the PWM control strategy, the inverter output voltage and frequency can be controlled uniformly through a single converter control, unlike the conventional methods of Variable Voltage Input control (VVI) and Variable Voltage Output control (VVO) inverters and also the switching technique using the phase shift control.

With the wide-spread availability of VLSIs, better PWM schemes and Sampled PWM schemes like those using Marconi MA818 ASICS chips have become feasible [7,15,23-25,27-29,33]. Although, these are conceptually more involved hardware designs; these chips are more compact and reliable. Following are some of the points, which are worth noting:

- In past analog circuits have been used to generate sine waveform and to compare it with the carrier, to generate firing coordinates for power semiconductor devices. Three of such waveforms 120^{o} displaced from one another were felt necessary for a three-phase inverter output. The amplitude of the output fundamental has been varied by varying the amplitude of the modulating signal (Sine Wave) to vary the value of 'M'. However, varying the value of 'I' has made it necessary to vary the frequency. Both of these variations have conventionally been done in the analog circuit.

- In order to avoid the complex method to generate sine wave, a stepped or trapezoidal or some other waveforms e.g., DC level modulation are used. Otherwise the Sampled PWM has been more commonly practiced.

- Hybrid circuit schemes, where the firing coordinates are obtained by digital comparison of carrier and modulating signal have also been in practice in order to simplify the problem.

- The firing coordinates obtained in any of the above noted schemes can be computed a priori [19, 23-25]. These firing sequences can be stored in look-up tables in 'ROM' to be accessed any time for the necessary control of voltage and frequency. Typical possible criterion is elimination of a selected set of harmonics in the output for a given application.

The last two methods are digital and are implemented with microprocessor based inverter systems only. They give more precise harmonic elimination. The last one calls for detailed computation at the design stage itself. But undoubtedly, it yields the best results. Specifically with a given number of switching, maximum harmonic elimination is achieved. However, the 3n+2 harmonics can be eliminated with n pulses per half cycle. In addition, the third and multiples of three harmonics will remain essentially ineffective in a three-phase system [17,19].

All of the above schemes will be studied in detail and extensively researched upon, keeping in mind the application of scope of the research topic **"***Protection and Health Monitoring of IGBT Based PWM Inverter Fed AC Drive Systems*".

3.3 Existing Protection Schemes

Protection offered by AC drives is broadly of three types –

- Inverter related.
- Motor related.
- Load related.

Mechanical stresses, process requirements etc. may require the drive to accelerate &/or decelerate at specified rates. These are normally ensured by the drive by changing the supply frequency at a specified rate. Upper load limit may have to be limited at a specified value. Identifying the corresponding maximum load current through the motor and keeping it within the identified limit does this job. In short, the load related protection features are acceleration & deceleration rate upper load limit [5,27,36].

Motor related protection features are well established.

- Thermal protection executed by realizing inverse time current curve. Many of today's drives realize this in software and do not use a separate thermal overload relay.
- Overload (current) protection realized by comparing the load current with a set upper limit & taking protection action.
- Upper speed limit. This can be load-related protection also. It is realized by the drive not accepting set speed above the specified limit.
- Supply voltage to the motor is limited to avoid over fluxing & related problems.
- Unbalance in motor current is kept in check. In comparatively high power drives (>100Hp), this is realized by computing the negative sequence component of current & keeping it within limits. In smaller drives, this is done in an indirect manner by checking the ripple current level in the DC link.
- Under-voltage related protection by comparing DC link voltage against a lower set limit and taking necessary protection action.
- Earth leakage protection is not provided in small drives. But as the power capacity increases (>50HP etc.), it becomes necessary. It is realized with the provision of an Earth Leakage Relay.

A well-designed and engineered drive would ideally be fool proof and does not require protection [5,27,36]. Such an approach to drive has been adopted by very few manufactures

(they do not provide any separate protection to all). However, almost all manufacturers treat the above as hypothetical and have the following built in protective features:

- Short circuit protection for the PSD: This is built in as part of the base/gate drive of PSD. The PSD is turned off on short circuit.
- Thermal protection for the PSD: The heat sink temperature is measured and in case it exceeds an upper set limit, the drive is switched off.
- Protection against unequal voltage distribution in filter capacitors: DC link filter capacitor bank comprises of a number of capacitors. Any unbalance in voltage distribution is hazardous to the capacitor and hence it is to be avoided.
- Fast acting fuses in DC link and AC supply line provide short circuit protection at the respective points.
- DC link over voltage protection: This is necessary to avoid overstressing of PSDs.
- Watchdog protection for the microprocessor: In case of microprocessor failure, the drive operation can get paralyzed [37]. To avoid this eventually, the watchdog keeps a close watch on the microprocessor. In case of its failure, the watchdog circuit gives out an alarm or enables a contact or relay which can be used to initiate emergency follow up. The watchdog circuit also shuts down the PSDs, Contactors, etc. In case of over voltage, the main contactor of the drive may be turned off to protect all the rest of the devices. In all other cases, the PSDs may be turned off and the contactor left undisturbed.

Protection is realized at various levels. All load and motor related protection activities can do with protection through the microprocessor. The protection signal interrupts the processor and seeks action. The associated delay will be of the order of a few microseconds. This delay is tolerable here. In contrast, the drive related protection has to be faster. For example, over current/short circuit protection for the PSD has to act within a microsecond. In these cases separate protection hardware is built-in. Very often, after initiating protection action locally, they ‘inform’ the processor of the same. The processor may disable the drive completely. Operation is resumed after operator clears the fault and the processor is ‘told’ of the same through a Reset Signal.

Although, the research work reported in the published papers [30-37] is devoted to the design and development of protection circuit for specific applications and has been successful; the research proposal envisaged to be pursued in this dissertation adopts a further step forward to have an integrated approach to investigate, design and develop a complete generic design strategy for the implementation of such circuits with complete Protection and Health Monitoring Control of Variable Speed AC Drives. More research papers as envisaged shall be referred to during the course of the research work.

4. Problem Identification/Objectives

Every protection system should fulfill the basic system requirements. Therefore, the main objective of this research work is to design an adequate protection system keeping in mind the following relevant points:

a) The prospective protection system should be able to identify all kinds of faults and should also be able to identify the difference between momentary over current and over-load and/or short-circuit conditions.

b) The detection and interruption of fault should be very fast, so that the fault is not able to cause any damage to the PSDs and also to the connected control equipment.

c) The system should be able to differentiate between the fault current and starting current in case of motor control application.

d) After detecting the fault, the system should be able to diagnose and display the cause of the fault, so as to reduce the trouble shooting time and to educate the operator.

Further, it may be emphasized that the Power Semiconductor Devices inherently have limitations of very low thermal mass and extremely low surge withstand capability, as compared to that of the heavy Electrical Equipment. Hence, there has arisen the need for the design, development and study of more versatile and fast acting Intelligent Knowledge Based Protection System, in conjunction with large safety margin ratings to ensure system reliability vis-à-vis the costs of device failure leading to disruption in production and hence further losses.

The new research proposal of this dissertation envisages taking a further step forward towards an integrated approach to investigate, design and developing a complete generic design strategy for the implementation of such circuits with complete Knowledge Based Intelligent Control.

5. Methodology To Be Adopted

The research methodology adopted in the proposed dissertation shall consist of the following:

i. Study of various features of PSD's especially that of the IGBTs and its conventional protection circuits as well as the PWM Voltage Source Inverter system.
ii. Literature survey of the latest trends available in PWM Inverters and Health Monitoring of Squirrel Cage Induction motor Drives.
iii. Design Development and Testing of Protection Systems for PSDs and Health Monitoring of drive systems.
iv. Integration of the protection system and that of Health Monitoring circuits thus designed and developed with the power circuit.
v. Testing and trials using PWM inverter fed Variable Speed AC Drives.

6. Proposed/Expected Outcome Of The Research

The outcome of this dissertation entitled "*Protection and Health Monitoring of IGBT Based PWM Inverter Fed AC Drive Systems*" shall be to give a complete and reliable protection for the Inverter and Health Monitoring to the Variable Speed AC drives with complete protection schemes. It may be possible to get at least three full research papers and one intellectual property right (IPRs) from this dissertation.

7. Proposed Time Frame

The proposed research work will be completed in the following phases:

Phase I – Course work & Literature Survey of the broad area of research.

Phase II – Literature survey of the latest trends available in IGBT Device Protection & Health Monitoring of Voltage Source PWM Inverter fed Induction Motor.
Study of the past and present status of Variable Speed Drives.

Phase III – Study of various characteristics and applications of IGBTs.
Concluding on the requirements of an adequate protection system.

Phase IV – Design and development of a IGBT protection system.

Phase V – Analysis of results and thereby concluding on the failure mechanism and reliability of protection.

Phase VI – Design, Development and Comparative study of Health Monitoring circuits. Laboratory testing of the newly designed circuits.

Phase VII – Writing of Thesis.

It is envisaged that the research work will progress as per the detailed plan.

8. References

[1] L. J. Penkowski & K. E. Pruzinsky, "Fundamentals of a Pulse Width Modulated Power Circuit", IEEE Transactions on Industry Applications, Vol. IA-8, September/October, pp. 584-592, 1972.

[2] F. F. Mazda; Thyristor Control: Newness-Butterworth, England (UK), 1973.

[3] Csaki, Gansky, Ipsist and Marti; Power Electronics. Budapest: Academic Press, 1975.

[4] S. B. Dewan and A. Straughen; Power Semiconductor Circuits, Wiley Inderscience, 1975.

[5] C. M. Bhatia, "A Report on Pulse Width Modulators", Technical Report, Indian Institute of Technology Delhi, New Delhi (India), May 1976.

[6] S. D. Gupta, "On Thyristorised PWM Inverters", M. S. Dissertation, Queen's University, Kingston, Canada, 1976.

[7] P. C. Sen, S. D. Gupta, "Modulation Strategies of Three-Phase PWM Inverters: Analysis and Comparative Study", Canadian Electrical Engineering Journal, Vol. 4, No. 2, pp. 13-20, 1979.

[8] T. L. Grant & T. H. Barton, "Control Strategies for PWM Drives", IEEE Transactions on Industry Applications, Vol. IA-16, pp. 211-216, March/April 1980.

[9] GE SCR Manual, Sixth Edition, General Electric, Prentice-Hall Inc., Englewood Cliff, New Jersey, 1982.

[10] B. K. Bose and H. A. Sutherland, "A High Performance Pulse Width Modulator For An Inverter Fed Drive System Using A Microcomputer", IEEE Transactions on Industry Applications, Vol. IA-19, pp. 235-243, March/April 1983.

[11] B. Jayant Baliga and Dan Y. Chen, "The Insulated Gate Transistor (IGT) – A New Power Switching Device", Power Transistors: Device Design And Applications; IEEE Press, 1984.

[12] G. K. Dubey, S. R. Doradla, A. Joshi, R.M.K. Sinha; Thyristor Power Controllers; John Wiley & Sons (India),1985.

[13] B. K. Bose; Power Electronics & AC Drives, Prentice Hall, (USA), 1986.

[14] W. Shepherd and L. N. Hulley; Power Electronics and Motor Control; Cambridge University Press (UK), 1987.

[15] S. K. Sethuraman and M. A. Waheed, "PWM: A Survey of Modulation Strategies, Their Spectrum Analyses and Microprocessor Implementation", 22nd University Power Engineering Conference, Sunderland Polytechnic (UK), 1987.

[16] A. K. Wahi, C. M. Bhatia, R. Arockiasamy, "Microprocessor Controller for the Wound Rotor Induction Motor, Using Rotor Chopper Control", VNPSC' 81; Fifth National Power Systems Conference; Bangalore (India), September, 1988.

[17] C. M. Bhatia, M. M. Ektessabi, S. S. Lamba, "A Novel Microprocessor Based Modulator for PWM Inverters"; 23rd Universities Power Engineering Conference, Trent Polytechnic Nottingham (UK), September 1988.

[18] C. M. Bhatia, A. K. Wahi, R. Arockiasamy, "Extension of Torque Control Range of Microprocessor Controlled Wound Rotor Induction Motor Using Rotor Chopper Control"; 23rd University Power Engineering Conference Trent Polytechnic, Nottingham, (UK), September 1988.

[19] M. M. Ektessabi, C. M. Bhatia, S. S. Lamba. "A Modified Natural Sampling Strategy for Microprocessor Implementation of PWM Inverter"; IECON '88, 14th Annual Conference of IEEE Industrial Electronics Society, Singapore, October 1988.

[20] A. K. Wahi, C.M. Bhatia, R. Arockiasamy; "Design and Development of a Transistor Chopper for Rotor Control Of Induction Motor"; IECON 88, 14th Annual Conference of IEEE Industrial Electronics Society, Singapore, 1988.

[21] M. H. Rashid; Power Electronics: Circuits, Devices and Applications; Prentice Hall, USA, 1988.

[22] G. K. Dubey; *Power Semiconductor Controlled Drives*, Prentice-Hall, USA, 1989.

[23] M. M. Ektessabi, C. M. Bhatia, S. S. Lamba, "A New Software Strategy for Microprocessor Implementation of PWM Inverters", ISMM Conference; California December, 1989

[24] C. M. Bhatia, "Feasibility Studies on Design of a 2 Megawatt Separately Excited DC Motor Speed Controller for Electrical Propulsion of DC Battery Supply", An Industrial Consultancy Project Report Submitted to IIT Delhi, March/April 1992.

[25] M. M. Ektessabi, C. M. Bhatia, S. S. Lamba; "A Dedicated Digital Implementation of PWM Inverters", IASTED International Conference, July 8 – 10, 1992, University of Tehran, Tehran (Iran).

[26] R. S. Ramshaw, "Power Electronics Semiconductor Switches", Second Edition; pp 294-323; Chapman & Hall, London, 1993.

[27] C. M. Bhatia; "Design Development and Fabrication of MA 818 Controller for Three-Phase Voltage Source Transistorised PWM Inverter", Research Monograph Number IDESP/MAP/02/1993; Microprocessor Application Programme of IIT Delhi, 1993.

[28] C. M. Bhatia, M. S. Rao, S. N. Ali; "Spread Sheet approach on PWM Voltage Source Inverter fed induction motor", International Conference on Electric Machines (ICEM); September 5-8, 1994; Paris (France).

[29] C. M. Bhatia, M. S. Rao, Ali Salem Bathuniya, Pradeep Kumar, " Design Development and Fabrication of MA 818 controller for a Three-phase, 10 KVA, Voltage Source Transistorized PWM Inverter", Journal of IETE, Vol. 11, September - December 1994, pp. 341-346.

[30] Debaprasad Kastha and Bimal K. Bose, "Fault Mode Single-phase Operation of Variable Speed Induction Motor Drive and improvement of Pulsating Torque Characteristics", IEEE Transactions on Industrial Electronics, Vol. 41, No. 4, August 1994.

[31] Debaprasad Kastha, Bimal K. Bose, "Investigation of Fault Modes of Voltage-Fed Inverter System for Induction Motor Drive", IEEE Transactions on Industry Applications, Vol. 30, pp. 1028-1037. Aug. 1994.

[32] Rahul S . Chokhawala, Jamie Catt and Laszlo Kiraly, "A Discussion on IGBT Short-circuit Behavior and Fault Protection Schemes", IEEE Transactions on Industry Applications, Vol. 31, No. 2, March/April 1995.

[33] Motorola Semiconductor Application Note, AN1541, Introduction to Insulated Gate Bipolar Transistors, 1995.

[34] Amit Gupta "Fault Analysis of PWM Inverters", M. Tech Thesis submitted to the Department of Electrical Engineering, Indian Institute of Technology; Delhi, 1996.

[35] C. M. Bhatia and M. S. Rao, "Knowledge Based Protection Circuit for Converter and Inverter Applications", Intellectual Property Right; IIT Delhi 1997.

[36] Muhammad H. Rashid, "Power Electronics Handbook", Academic Press, 2001.

[37] J. Klima, "Analytical Investigation of an Induction Motor Drive under Inverter Fault Mode Operations", IEEE Proceedings Electrical Power Application, Vol. 150, No. 3, pp. 255- 262, May 2003.

[38] Fuji IGBT Modules Application Manual, REH984, Fuji Electric Drive Technology Co. Ltd., February 2004.

[39] C. M. Bhatia, Sangeeta Banga, Meenakshi Khurana, Sanjana Malhotra, Bhawna Juneja, Hanu Bhardwaj and Meena Kapahi, " Stand-Alone SCADA Based Renewable Energy Power Station Suitable for Rural Application", IETE Technical Review, Vol. 23, No. 5, pp 319-324; September-October, 2006.

[40] B. Salhi and A. Benfdila, "Recent Trends in IGBT Technology", African Physical Review, Special Issue (Microelectronics): 0009, 2008.

[41] B. Lu, S. Sharma, "A Literature Review of IGBT Fault Diagnostic and Protection Methods for Power Inverters", Proceedings of the 43rd IEEE Industrial Applications Society Annual Meeting (IAS"08), October 2008.

[42] International Rectifier Application Note, AN 983, IGBT Characteristics, July 2012.

[43] Newtons4th Ltd, Application Note - 017, PWM Motor Drives – Theory and Measurement Considerations, September, 2012.

[44] J. H. Choi, K. J. Hong, J. S. Park, B. G. Gu, C. Y. Won, "A new short-circuit protection scheme for small inverters", IEEE Vehicle Power and Propulsion Conference, October, 2012.